Advances in Grouting Technology
Applicable to Dam Construction and Repair

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Introduction

Questions about the effectiveness and the long-term performance of grouting, particularly foundation and abutment grouting at damsites have persisted over the years. In addition to this, there have long been questions as to where grout goes, what it is doing to the rock or the soil, and what changes in pressure and flow rates mean. And then there are the questions about grout mixes – how can you fill a void in rock with a grout mix that has more than 50 percent shrinkage and high water bleed? There have been tremendous advances in grouting technology in the past 20 years that involve two primary elements of this practice: the use of stabilized low/non-shrink grouts with viscosities previously unachievable, and the application of state-of-the-art computer technology to grouting.

Foundation grouting at dam sites in the past was primarily based on pumping thin mixes of portland cement grout and water into the subsurface through boreholes targeting joints and discontinuities in the hope that by filling these potential pathways, the adverse effect of seepage would be mitigated. The major difficulties in achieving “closure” or control of seepage in this manner is that the mixes used had to be thin enough to readily pump, and thin enough to flow through the cracks, joints, or fractures in the rock. To do this, the mixes were of relatively high water to cement ratios, and these grouts were mixes that, when cured, shrank, and had significant bleed associated with the separation of excess water from the cured grout. Advances in additives have made it possible to now use grouts that have essentially little or no shrinkage and very low bleed, with much lower water to solids ratios, yet are no more viscous than the old-style mixes of much higher ratios.

Another problem often plaguing grouters was the phenomenon of premature closure of grout holes. In the era of manually measured grout flows, readings were taken by inspectors at discrete time intervals, and by the time a hole was prematurely blocked or plugged, it was often too late to make adjustments and save it. With continuously monitored grouting, through computers, we can now monitor and make adjustments immediately in response to the behavior of grout in the subsurface to often prevent premature closure. We can also terminate grouting immediately when closure is achieved, or in response to undesired fracturing, uplift or leakage, without having to wait until the next reading interval for detection of these circumstances.

Literature Resources

Federal agencies in the U.S., notably the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation have produced manuals and guidance documents based on the experiences and protocols developed over the years, some of which are now readily available on-line. The Corps of Engineers 1984 Grouting Technology Engineering Manual is may be found at: http://140.194.76.129/publications/eng-manuals/em1110-2-3506/toc.htm. The Corps' Chemical Grouting EM may be found at: http://140.194.76.129/publications/eng-manuals/em1110-1-3500/toc.htm. Published works by experts practicing internationally (Clive Houlsby, Jim Warner, Donald Bruce and Kenneth Weaver, among others) are also available on the market, and present a wealth of information.

The newly-prepared U.S. Army Corps of Engineers Engineering Manual EM 1110-2-3506: Grouting Technology was undertaken as an update to the previous version of the manual, last published in January, 1984. The scope of its update is indicated in some sense by the increase in size of the document alone from 8 MB to 30 MB (159 pages to 640 pages.) The manual was prepared under A/E contract to Gannett-Fleming, Inc. with a number of people inputting portions of it, including David Wilson, Trent Dreese and Donald Bruce, of Geosystems, Ltd. The manual was reviewed by personnel of several Corps of Engineers districts, including Jacksonville and Chicago Districts.

Initiating Grouting Programs

Foundation grouting represents an often large and uncertain cost associated with dam construction and seepage remediation. We do not have the advantage of constructing the foundation bedrock or soil, so our information as to its condition can only be ascertained by borings. However well thought out any exploration program is, there is never complete certainty of what subsurface conditions are between borings. In some ways, the mental picture we get from borings may be likened to pixels of a digital image - and in this analogy, we are given a number of pixels equivalent to the number of borings, and asked to predict what the overall picture will look like. If we are fortunate, we have rock outcrops and road-cuts to look at that provide us with exposed rock surfaces of at least the uppermost bedrock and soils present, so we are not completely in the dark. But an exploration plan is important in the development of a grouting program.

Early stages of a site investigation remain relatively unchanged over the past 30 years or so, and exploration drilling and sampling methods have undergone some technological advances like all other areas of engineering – core barrels are a little better, diamond bit configurations have been improved, new methods, and drill rigs with greater mobility, variable inclination and better precision are available, but the methodology is essentially the same. Water pressure testing remains the initial tool in assessing the scope of grouting necessary to reach the desired foundation permeability, and the analysis of data collected during the testing remains the same – with the exception that most of the analysis is now done by software packages rather than hand calculations.

The site investigation borings, in combination with surface mapping of geology and literature research may provide ideas as to areas in which to locate borings for a test program. After determining the need to grout, a test program is often undertaken to evaluate the extent of need and to provide more data to estimate quantities and a grouting approach – number and array of holes, orientation and inclination, and preliminary mix design, as well as refining closure criteria.

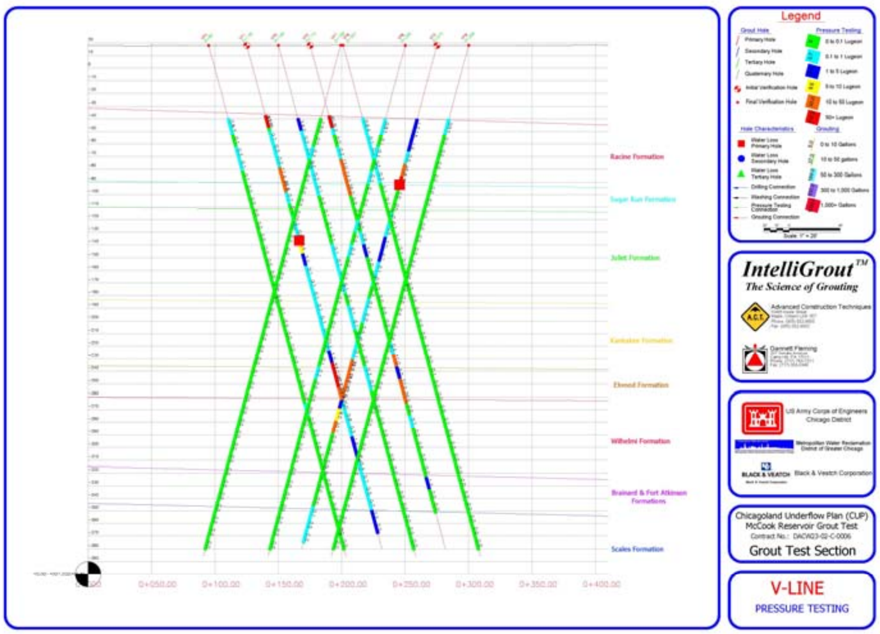
Depending upon the consequences of seepage, the design of the program may be adjusted to incorporate other methods of seepage control, such as positive cutoff walls, or collection/drainage systems, and the overall feasibility of grouting can be assessed in light of alternatives available. Once the decision is made to grout, the details of the design begin to take form.

Test Grouting Programs

If the scope of the seepage is such that it is deemed appropriate, an on-site test grouting program may be included as a phase of the overall grout work, or it may be a separate contract. The advantages in conducting the test grouting program as part of the production grouting contract include the continuity, savings on mobilization and demobilization costs, the site familiarity that will result from having the same contractor do both tasks (test grouting and production grouting), and continuity of means and methods developed during the test program that are then applied in the production phase. If a separate contract is used for each phase, the lessons learned may still be selectively used to improve the contract specifications, but aspects of the test program that were not cost effective may be more readily disregarded without incurring liquidation expenses for the contractor's costs associated with them. Additionally, it provides the owner with the opportunity to change contractors without prejudice or the need to terminate a contract, should there be a reason to do so.

An essential element of any test grouting program is to document every aspect of the work – regardless of field assumptions that means and methods may be common knowledge or that recollection will suffice to answer questions later. What might appear to be a trivial detail may become an important consideration in a production operation, be it water supply, control of waste streams, logistics, or availability of grout constituents. The task of preparing a lessons learned report may be born by either the contractor or the owner, but without a thorough final report, knowledge gained lasts only as long as the people involved remain associated with the project. In this era of digital imagery and electronic documentation, there is no excuse for not having complete documentation of this vital stage of major grouting operations.

The elements that may be included in a test program are the number, size, inclination/orientation and drilling methods for boreholes; the number and properties of grout mixes to be used; the grouting pressures, and development of effective and attainable closure criteria to meet project needs. For most applications where grouting is assumed to be feasible, a minimum double-line curtain array is appropriate. Where possible, and dependent upon prevailing joint set orientation, borings should be oriented to maximize the number of joints/discontinuities intercepted. If the test grouting program includes provisions to vary the orientation, the documentation of the relative effectiveness and the grout takes associated with different orientations should be carefully evaluated. An approach that has been used in the past 10-years or so is to orient the inclination of parallel rows of grout borings oppositely – to construct an array that has a diamond pattern when viewed in section – which minimizes the size of any potential gaps in the grout curtain. Logistical and structural aspects of the project may preclude this from being possible, and it is sometimes possible that the orientation of the structure is such that the optimum orientation of grout holes is not practical. In such cases, allowances for reduced effectiveness may be necessary.



This output from ACT's Intelligrout System™ shows the array of test grout holes in opposing orientation with water pressure testing results posted and graphically displayed.

Improvements in Grouting Technology

The improvements in grouting technology that have occurred over the 25 years since the 1984 Engineering Manual was written were beginning to appear even then. The 1984 manual includes an example grouting form that was used by this author at Clarence Cannon Dam in 1981. This form was designed to facilitate data collection on a mainframe computer program used to evaluate grout takes by mixes and pressures. In the case of Cannon Dam, the data were not analyzed until months after the grouting was completed, because the computer was located in St. Louis, 140-miles away, and the transfer of data was done manually from field sheets by a technician or geologist in the office. The grout takes were calculated in the field by manually measuring the grout in the sump tank of the grout plant at regular intervals and by dividing the difference between measurements by the elapsed time, a flow rate was determined.

By the mid 1980s, however, the beginnings of Computer Aided Grouting Engineering System (CAGES) were in place, and the development of microcomputers made the evolution of this to take off. As these systems developed, they began to include the capability to record grout take continuously – first as a tracing on graph paper, and then digitally on magnetic media. The use of magnetic flow meters has greatly improved the ability to measure flow rates continuously, as there are no mechanical moving parts that can become gummed up with grout. As things improved, systems were developed that would process the data that was recorded, and could concert it to apparent Lugeon values – the grouter's measure of permeability. Flow meters became more accurate, and it is now possible to accurately measure grout takes below 1 gallon per minute, whereas in 1981, we could not be more accurate than ½ cubic foot per minute with much confidence.

Grouting can now be controlled remotely, by computer, and results evaluated in real time

The drop in costs of display screens and color plotters, in combination with the improvements of graphics and database management software have resulted in the ability to collect data, evaluate it, and display it on a large-screen, transmit it electronically to a remote location, or plotted drawings virtually grouting is happening. Graphics software is now in use that displays data on water pressure testing and grouting to evaluate whether the grouting is continuing as expected based on water pressure testing, or whether there are inconsistencies. This permits decisions to be made and corrections in means and methods where appropriate in a far more timely fashion than before. This ability to process and display the results in real time allows decisions on split-spacing of holes, target zones of subsequent holes, and necessity for additional grouting to be made in far less time and with much greater confidence than was possible before.

Advances in Drilling

In areas of relatively low rock mass permeability, and in larger production size grouting projects, drilling represents a major cost item. Advances in drilling technology related to the needs of grouting programs have added to the effectiveness of grouting as a solution to foundation problems. In the case of existing structures, there is great concern raised over the potential impacts of conventional drilling methods, particularly in hydraulically lifting or hydrofracturing embankments. The increasing availability of sonic drilling methods has provided an alternative that produces grout holes that are often straighter and are drilled with a greater level of confidence that they are not causing one problem in an attempt to solve another. Another advance that has occurred in recent years is the development of smaller diameter water-actuated down-the-hole hammer drills, capable of accurately drilling holes to greater depths. A recent test program at the Chicago District's McCook Reservoir project produced satisfactory results (hole declinations within satisfactory limits, and while the deviation of this method was slightly higher than comparable rates using diamond core drilling equipment, stabilizers were not used. Subsequent developments of stabilizers are likely to mitigate this minor difference, and the advantage gained in the drilling rate may more than compensate for any cost differential.

The use of a hard-surfaced work platform and state-of-the-art drilling equipment make it possible to more accurately construct grout curtains of greater depths.

The advances in grouting technology now make it possible to evaluate data conclusively, and reach decisions as to whether or not to continue with more holes, how deep or shallow those holes should be, and what the expectations for grout takes are, essentially as the grouting is performed. So among the great improvements that have occurred in grouting technology are the accuracy, precision and timeliness of data collection during grouting, and the ability to process these data in real time, and display the results graphically and in tables as the grouting proceeds, thus allowing more timely and efficient decisions to be made.

Improvements in Grout Mix Design

Grout mix design is based on the ability to pump the grout and have it thin enough to pass through void spaces (discontinuities, joints, cracks or pore space) in the foundation materials. The study of non-Newtonian fluids, or fluids whose behavior with respect to viscosity, flowability, etc. is not constant is rheology. Neat (simple) water-cement grout behaves as a rheologically unstable fluid – its behavior changes dramatically as various environmental conditions change – particularly flow rate, turbulence/agitation, temperature, and pressure. When such mixtures flow at very low rates, they tend to prematurely increase in viscosity, and grouting can be interrupted or stop altogether when grout equipment clogs or discontinuities are prematurely blocked.

Concurrent with the improvements in the ability to manage and evaluate data from grouting, advances were being made in grout mix design. Fluidifiers and water reducing agents have been known to grouters for years, but were often quite expensive. The effectiveness and compatibility of various admixtures was also uncertain. Consequently, the design of grout mixes was a matter of making the mix thin enough to travel through discontinuities in the foundation materials enough, and relying upon the instability of the essentially water-cement mixture to segregate and the solid components to fill in the void spaces, while the bleed water was theoretically pressed out. The resulting mixes were often pathetically thin – from 5 parts water to one part cement up to even 10 to 1, and the material left in the rock was structurally weak, unstable, and not durable in the face of moving water. The bleed water from these weak thin grouts must go somewhere, and pumping a great deal of water into the ground is not an effective way of controlling permeability.

Great advances in admixtures - the better understanding of the properties of things like bentonite, welan gum and fluidifiers have made it possible to design mixes that have similar properties in terms of viscosity to the old 6 to 1 mixes, with ratios approaching 1 to 1, water to solids volume. Additionally, the designs now used are rheologically stable and the flow properties remain constant across a wide range of flow rates and pressures. This keeps grout moving at even very slow rates, where tight closure is an absolute requirement.

The tools of a grout inspector or geologist in the early 1980s included a notebook, a calculator, a watch and a dipstick, to measure the grout volumes in the sump tank. The current state of grouting is such that the grout plant and associated equipment takes care of data recording, and the tools are those used to monitor viscosity and specific gravity of the mix. Viscosity is measured with a drilling mud funnel, which accepts a liter of fluid, and the time it takes to drain is a measure of the viscosity of the fluid relative to water. By measuring the specific gravity and viscosity, the stability and appropriateness of the grout mix can be verified, while the monitoring equipment continues to collect and analyze the flow and pressure data. Flow rates are measured by magnetic flow meters. Grout components are measured by automated systems and weighed by load cells, accurately and precisely. Pressures are measured by automated systems using pressure transducers instead of mechanical spring gages.

In addition to the viscosity and fluid stability of grout mixes, the understanding that bleed-water is a problem with grouts has focused attention on reducing water content, as well. When the water content is reduced, there is less water for hydration of the cement, so additives may be necessary to facilitate the process of hydration. The water reducers now in use do just that – they reduce the surface tension on the surface of the cement particles, as wetting agents, and make it possible to use less water while achieving full hydration. Bentonite is a swelling montmorillonite clay that takes on water over time. If it added as a dry powder to grout, it will continue to take on water during mixing and pumping, and the properties of the grout will change in response to how much water the clay absorbs. Using pre-mixed hydrated bentonite slurries instead of adding it as a dry powder keeps the properties constant.

Understanding the flow properties during mix design, and monitoring them during grouting, makes it possible to utilize only grout mixes that will result in permanent and effective seepage control. In combination with the fluidifiers, water reducers and fillers, a stable, balanced grout mix results – one with flow properties and viscosities that were only achievable with highly unstable thin mixes of the past.

Advances in Grouting Concepts

Grouting used to be a greatly misunderstood craft – some even referred to it as an art. The ability to effectively pump cement and water into a hole where it couldn't be seen and have it somehow achieve goals you intended was a bit mysterious. There are hundred of articles in engineering literature on the art and science of grouting over the years. With the advances in technology and mix design, though, we now better understand what is going on. There may be researchers somewhere looking into tracking the movement of grout with the electronic equivalent of a doctor's stethoscope. Monitoring grout takes at very precise levels – even fractions of a gallon per minute, in combination with monitoring of foundations with tiltmeters and other instruments is starting to show us how the grout take signatures appear when different things are occurring. The grout take signatures are studied, and some are typical of the preferred progressive filling of a discontinuity, others are indicative of a breakthrough situation where grout has either moved joint filling and is now accessing additional areas of the subsurface or leaking to the surface somewhere, while still other signatures are typical of situations where the rock is being hydraulically fractured or uplifted. None of this was possible with crude manual measurement.

A logistical development in grouting that has become more prevalent in recent years is the use of a work platform. Previously, grouting was often conducted on bare ground of uneven topography. The use of a hard-surfaced work platform that may or may not be a permanent part of the project greatly increases productivity by providing easier equipment mobility and more accurate drill set up. An equally important aspect is that this platform makes control of runoff easier – and provides much greater worker safety.

Lastly, the acquisition method utilized in contracting for grouting has been evolving in the Corps of Engineers, and possibly other government agencies. The Low Bid contracts used in the past have required very specifically prescriptive contracts, developed by the designers, based on their knowledge and expertise in the subjects. As we become more oriented toward quickly executing contracts for work, and when we realize that technological advances and creative methods are making this and other types of work more effective, the Corps of Engineers has recognized that private contractors may be operating with means and methods that are far more cost-effective than those of prescriptive specifications. The concept of "Best Value" contracts, with trade offs of cost for value is now being applied to larger grouting contracts. Under this type of contract, the solicitation is prepared with plans and specifications that are somewhat more prescriptive than a purely results-based or design/build contracts, but the contractors are required to provide a submittal that includes a statement of their expertise, a description of their approach to various aspects of the project – prioritized by the designers, based upon the relative importance to the project, a description of their staffing and Quality Control procedures, along with their price/bid. The selection panel decides ahead of time what the weights of the factors listed in the solicitation are, and convenes to review the submittals, and a contractor is selected based on rankings of the technical considerations separately from cost - and when the two are combined, a Best Value decision is made. The selected contractor may not be the lowest cost, and it may not be the most technically superior approach, it will be the Best Value that meets the needs of the project. This method provides the government with the best job for the money, and allows contractors to demonstrate their superior knowledge of this very technical construction discipline.

Summary of Advantages of New Technology and Equipment

Review of grouting literature and project performance records have been performed in order to produce a new Engineering Manual on Grouting Technology for the U.S. Army Corps of Engineers. Advances paralleling advances in overall technologic advances have occurred, including computer applications, drilling improvements, and enhanced design and engineering evaluation. These advances have allowed a more sophisticated approach to foundation grouting to be applied, both in terms of design of grouting programs and soliciting contractors for this type of work. Drilling improvements allow more accurate and faster production, including the use of sonic and water actuated down-the-hole hammers to provide safer, faster and more accurate drilling of grout holes. Knowledge added by the careful monitoring of grout takes and pressures in real time make it possible to more effectively treat rock mass permeability. This capability allows us to modify pressures or flow rates, stop grouting the instant damage may be occurring or when grout is going where we don't want it, change mixes immediately, and may eventually make it possible to determine the path of grout in the subsurface. Evaluation of data in real time makes it possible to adjust the methods used in successive series of grout holes in a more timely manner. And the use of stabilized grout mixes will provide more permanent solutions to rock mass permeability issues. The goal of all this is to save time, materials and labor cost, while producing more permanent solutions to foundation permeability issues.

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